Frits Zernike--life and achievements

Ferwerda, H.A.

Published in:
Optical engineering

DOI:
10.1117/12.142941

Frits Zernike—life and achievements

Hedzer A. Ferwerda
Groningen University
Institute of Theoretical Physics
Nijenborgh 4
NL-9747 AG Groningen, The Netherlands

Abstract. We present a review of the life and work of Frits Zernike (1888–1966), professor of mathematical and technical physics and theoretical mechanics at Groningen University, The Netherlands, inventor of phase contrast microscopy.

Subject terms: phase contrast microscopy; diffraction gratings; statistical physics; optical aberrations; Zernike polynomials; optical coherence.

Optical Engineering 32(12), 3176–3181 (December 1993).

1 Introduction

Frits Zernike (Fig. 1) was a modest man and a dedicated researcher. Zernike's field of interest was classical physics. Though working in a period of rapid and exciting developments in quantum theory, he was not attracted to that area of physics. His heart was in the field of applications of concepts familiar in classical physics. This is an area of study that requires an independent critical mind and is not the road that leads to rapid fame and recognition. Recognition came to Zernike, but in the later stages of his career. Zernike was a typical example of a professor absorbed in his science. He was unassuming, was not sensitive to status, and preferred to work with one or two assistants. He did not seek fame or recognition. His sharp mind went straight to the core of a problem by asking the key questions. He was critical toward his own work and was only willing (often after being persuaded by his close associates) to publish his results. This self-criticism led to a number of outstanding publications that are still recognized as such today!

Zernike worked on many different subjects in physics. In this paper I concentrate mainly on his seminal work in optics.

Typical of Zernike's modesty, on his retirement as a professor of theoretical physics and technical physics in 1958,

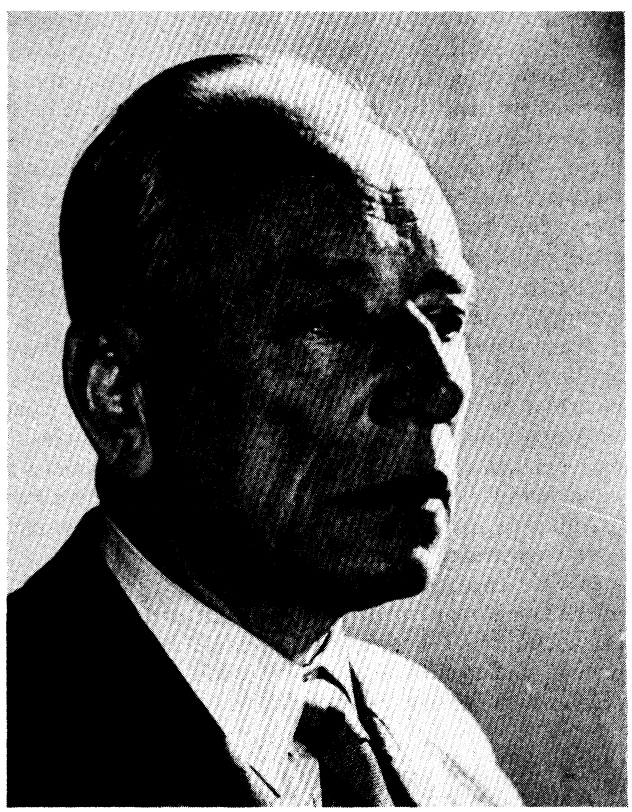

Fig. 1 Frits Zernike (1888–1966) (photograph courtesy of Universiteitsmuseum Groningen).

Paper PCM-01 received Oct. 19, 1992; accepted for publication Dec. 15, 1992. This paper is a revision of a paper presented at SPIE International Conference on Phase Contrast and Differential Interference Contrast, Oct. 1992, Warsaw, Poland. The paper presented there appears (unrefereed) in SPIE Proceedings Vol. 1846.

he presented a valedictory oration in which he did not even mention his achievements in optics, phase contrast, in particular! The text of this lecture has not been printed until recently. In 1988, Groningen University, the university to which Zernike was associated from 1913 until his retirement, organized a symposium in honor of the centennial of his birthday. On that occasion a booklet was published[1] that included the transcript of the valedictory lecture of Zernike, a valuable source of information about his life and achievements.

2 Biography of Frits Zernike

Frits Zernike was born on July 16, 1888, in Amsterdam, the son of Carl F. A. Zernike, headmaster and teacher at a public school in Amsterdam. His mother, Antje Dieperink, was also a school teacher. The atmosphere in the Zernike family was an intellectually inspiring one—one of his sisters became a well-known writer, while another became a vicar. He also had other relatives who became prominent scientists and intellectuals.

Zernike began his studies in chemistry in 1905 at the University of Amsterdam. In the meantime he passed the entrance examinations that were necessary for being permitted to take academic examinations. He passed them in 1906. His extraordinary faculties manifested themselves already at that time: as a student in chemistry he participated in a contest in the field of probability theory in 1907. The subject discussed was the "Clock and Hammer Game." His solution was crowned with a gold medal by Groningen University. He obtained the master's degree in chemistry in 1912 with the distinction *cum laude*. In the final phase of his study he again entered a scientific contest issued by the Dutch Society of Sciences in Haarlem, dealing with light scattering near the critical point of simple fluids and mixtures of substances. Professors Lorentz, Van der Waals, and Haga highly praised his answer, which would have won him another gold medal, if Zernike had not preferred to receive his prize in cash. This winning contribution was the basis for his thesis "L'opalescence critique, théorie et expériments," which he defended at the University of Amsterdam on February 17, 1915. He obtained the doctorate degree in chemistry again with the predicate *cum laude*.

In the meantime his abilities had been noticed by the famous astronomer, J. C. Kapteijn, who headed the Astronomical Laboratory at Groningen University. He appointed Zernike as an assistant, a post he was to hold from early 1913 until the middle of 1915. His appointment brought him into contact with the associate professor ("lector") of theoretical physics, L. S. Ornstein. They collaborated in the field of statistical physics (Ornstein-Zernike theory). In 1915 Ornstein became a full professor at Utrecht University and Zernike succeeded him at Groningen in June 1915. His educational assignment was mathematical physics and theoretical mechanics. In April 1920 he was promoted to a full professor with the same task. In 1941 the name of his chair was changed to mathematical and technical physics and theoretical mechanical engineering.

During the academic year of 1938 to 1939 he was the rector magnificus of Groningen University. In 1946 he was appointed member of the Royal Dutch Academy of Sciences. He had frequent contacts with his colleagues in academia and (optical) industry in The Netherlands. He made many trips abroad to attend conferences where he was a much sought-after speaker; he was an honorary member of the Optical Society of America. He often visited the United States on invitation (1922, 1947–1948, 1951, 1954). From 1947 to 1948 he was a visiting professor at Johns Hopkins University in Baltimore.

The most glorious event of his career was the award of the Nobel Prize of Physics in 1953 for his invention of the phase contrast microscope. Zernike had a broad range of interests: he had an early interest in religious matters, and after the second world war he joined the Humanistic Association. He also was active designing experiments for secondary schools. He often acted as an external expert in physics during the final examinations of secondary schools.

3 His Scientific Oeuvre

Zernike possessed a rare combination of skills: besides being a gifted mathematician, he was a genial experimenter and technician. On top of that he had a good knowledge of the performance of instruments. When a lathe broke down in the workshop of the laboratory, Zernike was the ultimate resource for fixing it.

In his scientific oeuvre we can roughly distinguish four different periods: keep in mind that this categorization is artificial and that these periods overlap:

1. 1911–1930, when Zernike worked mainly theoretically on statistical problems
2. 1930–1942, when he worked on physical optics; this was the period when he invented the phase contrast microscope
3. the period just before and during the Second World War when he worked on the wave theory of image formation in the presence of aberrations
4. the period after the Second World War, which was also devoted to the perfection of the phase contrast microscope and is in a certain sense an extension of period 2.

Let me review the different periods in more detail. I am rather brief about the first period. During this period he collaborated with Ornstein and Prins on problems of statistical mechanics. The Ornstein-Zernike and Zernike-Prins theories have not been forgotten in the physics of today. With Ornstein he worked on fluctuation phenomena. With Prins he worked on the formation of swarms and correlation functions. The correlation functions would recur in connection with the coherence functions in optics. In 1928 he wrote a highly original article on "Wahrscheinlichkeitsrechnung und mathematische Statistik" ("Probability theory and mathematical statistics") in the *Handbuch der Physik* (*Handbook of Physics*).[2] Simultaneously, Zernike had a strong interest in physical instruments. He was eager to show how the performance of instruments, whose inventors claimed to have achieved the ultimate possible performance, could be surpassed. An example is the very sensitive Zernike galvanometer,[3] which was exhibited at the World's Fair of New York in 1939. Zernike remained interested in statistical physics also during the second period. In 1940 he published an article on order/disorder transitions in crystals.[4]

The activities for which he is best known are in the field of physical optics. According to Zernike himself,[5] the foundations for phase contrast were not laid when working with a microscope but when experimenting with diffraction gratings, which were important in spectroscopy. This field was of interest to Zernike because of his spectroscopic work on oxygen, as he mentioned in his farewell lecture in 1958. Diffraction gratings consisted of a plane or concave mirror on which lines had been ruled by a mechanical ruling machine. Inevitably, this machine had some imperfections that led to irregularities in the spacing of the grooves. These irregularities manifested themselves as satellites (''ghosts'') of the principal lines. Interference between the principal line and its ghosts gives rise to fringes that were correctly identified as such by H. S. Allen in a 1902 paper. However, Allen dismissed these fringes as unreal, because they disappeared as soon as the ghost lines were intercepted. Zernike[5] repeatedly strongly objected to this statement because, according to him, these fringes contained information on the imperfections of the ruling machine. This remark ultimately resulted in the phase contrast method. A simple physical calculation is given to make this clear. We also show that this marked the beginning of holography (via the technique of coherent background). The invention of the phase contrast method was a leap forward based on a well-known theory namely, Abbe's theory of image formation in the microscope. However, the proper connections had never been made. Quoting Zernike in his *Science* article ''How I discovered phase contrast''[5]:

> How quick we are to learn—that is, to imitate what others have done or thought before, and how slow to understand—that is, to see the deeper connections. Slowest of all, however, are we in inventing new connections or even in applying old ideas in a new field.

In the case of the ghosts, the crucial observation was that the phase of the ghost line differed from the phase of the principal line. Let me explain this in terms of a simple model of an imperfect diffraction grating.

The imperfect diffraction grating can be modeled as an amplitude grating (which is the ideal grating) on which a phase grating with a coarser structure has been superposed. The latter represents the imperfections caused by the ruling machine that lead to a redistribution of the diffracted intensity, but do not lead to absorption. If we consider an amplitude reflection grating, the complex amplitude directly after reflection from the grating can be modeled by the amplitude reflectance function (for simplicity, we assume only one transverse dimension x):

$$r(x) = \left[a + b \ \sin\left(\frac{2\pi x}{d_i}\right) \right] \cdot \exp[i\phi(x)] \ . \tag{1}$$

The first factor describes the ideal amplitude grating with the grating constant d_i, while $\phi(x)$ describes the phase shift caused by the ruling machine, and a and b describe the background and modulation depth, respectively. Assuming that $\phi(x) \ll 2\pi$, $\exp[i\phi(x)]$ is approximated by $1 + i\phi(x)$. The function $\phi(x)$ is a periodic one for which we assume the simple model expression:

$$\phi(x) = m \ \sin\frac{2\pi x}{d_r} \ , \ m \ll 1 \ , \tag{2}$$

where d_r denotes the coarse periodicity caused by the ruling machine; the modulation depth m is taken to be small compared to unity.

The amplitude reflectance of the diffraction grating can now be expressed by

$$r(x) = a + b \ \sin\left(\frac{2\pi x}{d_i}\right) + im\Bigg(a \ \sin\left(\frac{2\pi x}{d_r}\right) + \frac{1}{2}b\left\{ \cos\left[2\pi x\left(\frac{1}{d_i} - \frac{1}{d_r}\right)\right] - \cos\left[2\pi x\left(\frac{1}{d_i} + \frac{1}{d_r}\right)\right]\right\}\Bigg) \ . \tag{3}$$

The first two terms describe the ideal amplitude grating, and the remaining terms are due to imperfections. If the reflection grating is placed in front of a lens, the complex amplitude in the back focal plane is the Fourier transform of $r(x)$, and yields diffraction spots in the positions $\xi \propto d_i^{-1}$, d_r^{-1}, and $d_i^{-1} \pm d_r^{-1}$ (ξ denotes the coordinate in the focal plane; proportionality constants are omitted). So in this simple example we see the occurrence of three ghost lines, of which the strength is determined by the modulation quantity m. We also note that the ghosts are 90 deg out of phase with the principal line. So Zernike was correct when he insisted on the importance of the physical phenomena hidden behind the ghosts! This observation ultimately led to the concept of phase contrast.

Let us turn to the experiments that Zernike performed. If we calculate the complex amplitude in the Gaussian image plane of the lens, this amplitude is a replica (up to a scaling factor) of the complex amplitude of the object. Because only the intensity can be recorded, we observe only the ideal image: the image intensity $I_i(x_i)$ is proportional to

$$[a + b \ \sin(2\pi x/d_i)]^2 \ .$$

The fringes caused by the interference between the principal line and its ghosts are gone. This was observed experimentally about 1930 when the laboratory where Zernike worked obtained a large concave grating ruled by Wood and installed in a Runge-Paschen mounting. It had been installed in a rather large room in the basement that was free from vibrations. So Zernike had a large space to work in. Therefore, he took the opportunity to point a small telescope to the Wood grating to see what happened to the ghost stripes. When the telescope was focused on the grating, the stripes were gone. They appeared when the telescope was focused at a plane in front of the grating. At the time of his experiment this was a big surprise, which was only understood after further experiments and calculations.

Zernike was quick to recognize the importance of the phases of the ghosts. It was commonly believed that phases in optics could not be observed because the detectors were quadratic ones. Zernike showed that phases could yet be made visible by introducing a coherent background. He performed the following experiment: he took a slit in a screen covered by a glass plate on which a thin metallic layer had been deposited that only transmitted a small percentage of the incident light. Next, he made a scratch in the metallic film that transmitted all the light incident on the scratch. The light on the scratch gave rise to a diffraction pattern that interfered with the light transmitted by the metallic film: the latter is the coherent background and would be called the reference wave in holography. Today we know that phases can be recorded in this way.

The step from the ghost lines to microscopy was conceptually a small one; its consequences, however, were enormous: Now for the first time one could see phase objects without having to stain them, a procedure that altered their structure in an uncontrollable way. Moreover, it was now possible to study living cells and tissues. The imaging of a phase object can be understood by replacing the grating by a phase object whose transmittance function can be represented by $t(x)=\exp[i\phi(x)]$. Assuming small phase shifts $\phi(x)$, $t(x)$ can be approximated by

$$t(x)\cong 1+\ i\phi(x)\ . \tag{4}$$

In the back focal plane we obtain the Fourier transformation of Eq. (4) that reads

$$u_f(\xi)=\delta(\xi)+i\hat{\phi}(\xi)\ , \tag{5}$$

where $\hat{\phi}(\xi)$ is the Fourier transform of $\phi(x)$, $\delta(\xi)$ is the unscattered wave that provides the coherent background, while $\hat{\phi}(\xi)$ contains the information about the object. It is well known that in the Gaussian image plane no modulation of the intensity is observed. However, when advancing or retarding the unscattered wave, preferably by 90 deg because the effect is most dramatic at that value, Eq. (5) becomes:

$$u_{f.ph}(\xi)=i\delta(\xi)+i\hat{\phi}(\xi)\ , \tag{6}$$

corresponding to an object with transmittance

$$t_{ph}(x)=i+i\phi(x)\ . \tag{7}$$

The intensity distribution in the Gaussian image is now calculated according to

$$|t_{ph}(x)|^2=1+2\phi(x)\ . \tag{8}$$

The 90-deg phase shift of the unscattered beam was achieved by Zernike by inserting a phase plate in the back focal plane at $\xi=0$.

The difficulties in observing phase objects were well known in Zernike's time: Otto Lummer wrote a treatise on Abbe's theory in which he explained why phase objects do not give rise to intensity variations in the image plane. The spirit of the work was that this was an inevitable fact of life that one had to live with. The practicing microscopist, usually not educated in optical image formation theory, found a way around this—by defocusing the microscope he could observe contrast. That his image was not a faithful replica of the object remained unnoticed. The defocusing played the role of Zernike's phase plate. Zernike fully appreciated the possible impact of his phase contrast method to the practical microscope: When the phase contrast method was still in its infancy, in 1932 he traveled to Carl Zeiss Optical Works in Jena, Germany. His method did not evoke the enthusiasm he expected. At Zeiss it was believed that everything that had to be known about microscopy was known since the fundamental work by Abbe. In 1890 Abbe became the sole proprietor of Zeiss and did not have the time and mind to work on problems in microscopy, because he had become absorbed in matters of managing and social problems. Abbe's successors apparently did not recognize the fundamental importance of phase contrast microscopy to laboratory practice. Another obstacle was the fact that Abbe's theory, while recognized as a landmark in image understanding by the physicists, was not accepted by the biologists who found his theory too abstract and probably out of touch with reality, because it also failed to explain the imaging of phase objects. So Zernike met a wall of skepticism and went home without having convinced those at Zeiss to turn their attention to phase contrast. They might have easily adapted their microscopes to include phase contrast—all that had to be done was to insert a ring-shaped diaphragm in front of the condenser and a phase plate in an intermediate image plane (the back focal plane in my simplified treatment). Zernike patented his invention[6] and wrote some papers on phase contrast.[7–9] Reference 7 was the first major publication on phase contrast. Contrary to what might be expected, this article was not devoted to microscopy but to the improvement of the knife-edge test of convex mirrors. In the same publication the circle polynomials were introduced that were to play such an important role in the wave theory of aberrations.

I now tell about the fate of the phase contrast microscope. The optical industry did not express much interest. It seemed as if the project was dormant. Apparently, interest revived with Zeiss during the war. This became clear when Zernike was visited by Colonel A. T. Brice, an optician, himself, associated with the firm Phase Films, Ross, California. Brice and another optician, C. P. Saylor from the National Bureau of Standards, Washington, D.C., were members of the special American contingent that evaluated the activities of the optical industry in Germany during the war. Immediately after the liberation they traveled to Groningen to inform Zernike about the great developments of his phase microscope that had taken place at Zeiss. This marked the beginning of close ties between Zernike and opticians from England and the United States. With Brice and Saylor, Zernike developed microscopes of variable contrast and color phase contrast. In the latter instrument phase differences are represented by differences in color.[10] Automatically, we have arrived at the fourth period of his research, which marked the improvement of the phase contrast method.

In 1953 Zernike was awarded the Nobel Prize in physics for his invention of the phase contrast microscope (Fig. 2). His Nobel lecture "How I discovered phase contrast,"[11] gives a good insight into how the concept of phase contrast took shape. The present presentation draws heavily on this source.

Another field of research to which Zernike made epochmaking contributions is the theory of optical coherence. His first publication on this subject dates from 1938.[12] His line of approach made coherence theory tractable from an application point of view. The merit of the paper mentioned was to use concepts directly related to observable quantities such as visibility of interference fringes. Unlike Van Cittert,[13] who used explicitly the probability density distributions of the

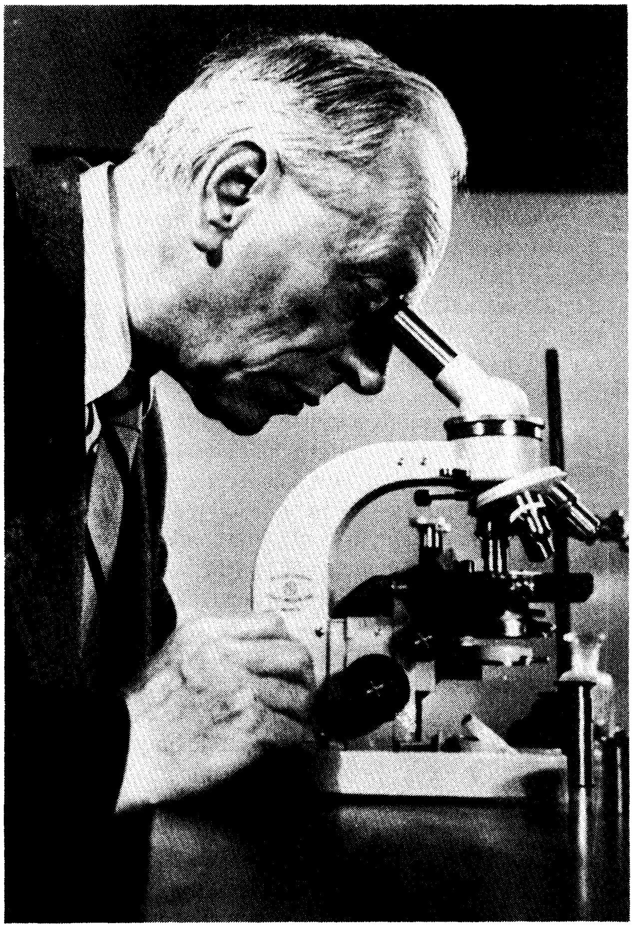

Fig. 2 Frits Zernike and his most glorious invention—the phase contrast microscope.

electromagnetic fields, Zernike focused on the correlation functions, which he called the degree of coherence. He showed that for any extended light source the degree of coherence only depends on the aperture of the illuminating light cone, and is not affected by the use of a condensing lens. As the resolving power only depends on the degree of coherence in the case of critical illumination,[14] this is a very practical result, because it tells us that one wastes one's money by choosing a well-corrected condenser lens. This paper also contains the derivation of what is now known under the name Van Cittert-Zernike theorem. This theorem had earlier been derived in a more complicated way by Van Cittert.[13] Later E. Wolf[15] and coworkers extended the coherence theory considerably. Coherence is still an important topic in modern research as evidenced by the discovery of the Wolf shift in 1986.

The third period extends roughly between 1940 and 1950 and was devoted to the image formation in the presence of aberrations. Zernike started this research[7] already in 1934 when he studied the change of the Airy diffraction pattern under the influence of small aberrations. This work was to be an improvement of the conventional treatment of aberrations, which is based on geometrical optics. This theory becomes unreliable when the radius of least confusion becomes comparable to the radius of the Airy disk.

Zernike's first paper on phase contrast[7] already contained the mathematical instrument for handling this problem—the Zernike circle polynomials. It turned out that these polynomials automatically take into account the balancing of the different orders of aberrations! They still play a significant role in lens design. The theory was developed for not too large aberrations by Nijboer[16] in his 1942 Groningen thesis, completed under the direction of Zernike. The case of large aberrations proved to be analytically untractable. Therefore, this case was studied experimentally by Nienhuis,[17] a graduate student of Zernike, who defended his thesis in 1948. His beautiful aberration figures have been reproduced in Ref. 14. The remaining problem was to find an asymptotic expansion for large wave numbers. This problem was tackled by Zernike's assistant N. G. van Kampen using the method of stationary phase that had to be extended to two dimensions. This fit well with the interest of Zernike's Groningen colleague of mathematics, J. G. van der Corput, who worked on the rigorous mathematical formulation. An interesting account of this can be found in a lecture on Thomas Young that Zernike[18] delivered on September 24, 1947.

4 Awards, Distinctions

Zernike was honored on numerous occasions. Admittedly, recognition came to him at a rather late age. The most important distinction by far was the 1953 Nobel Prize in physics. The other awards are:

- Honorary Fellow of the Royal Microscopical Society (1950)
- the Rumford Medal of the Royal Society of London (1952)
- Honorary Member of the Optical Society of America (1955)
- the Snellius Medal of the Society of Physics, Medicine and Surgery (Genootschap van Natuurkunde, Genees- kunde en Heelkunde) (1955)
- Foreign Member of the Royal Society (1956)
- Honorary Doctorates from the Universities of Amsterdam (1953), Poitiers (1955), and Modena (1963) [He could not receive the Honorary Doctorate of the University of London (1954) because of a guest-professorship in the United States]
- Dutch Royal distinctions (1952 and 1954), French distinction.

Frits Zernike died after a long illness on March 10, 1966.

References

1. H. Brinkman, Ed., *Frits Zernike, Groninger Nobelprijsdrager,* North-Holland Publishing Company, Amsterdam (1988) (in Dutch).
2. F. Zernike, "Wahrscheinlichkeitsrechnung und mathematische Statistik," in *Handbuch der Physik,* Geiger-Scheel, Eds., pp. 419–492 (1929).
3. F. Zernike, "Een nieuwe, zeer gevoelige galvanometer met beweeglijken draadklos" ("A new, very sensitive galvanometer with movable spool frame"), *Proc. Kon. Akad. Wet.* **24,** 239 (1922).
4. F. Zernike, "The propagation of order in cooperative phenomena," *Physica* **7,** 565–585 (1940).
5. F. Zernike, "How I discovered phase contrast," *Science* **121,** 345–349 (1955).
6. F. Zernike, Deutsches Reichspatent No. 636168 (September 1936).
7. F. Zernike, "Beugungstheorie des Schneidensverfahrens und seiner verbesserten Form," *Physica* **1,** 689–704 (1934).
8. F. Zernike, "Diffraction theory of the knife-edge test and its improved

form, the phase-contrast method,'' *Monthly Roy. Astron. Soc.* **94,** 377 (1934).
9. F. Zernike, ''Phase contrast, a new method for the microscopic observation of transparent objects,'' *Physica* **9,** 686–698 (1942); *Physica* **9,** 974–986 (1942).
10. F. Zernike, ''Color phase-contrast microscopy: requirements and applications,'' *J. Opt. Soc. Am.* **40,** 329–334 (1950).
11. F. Zernike, ''How I discovered phase contrast,'' *Les prix Nobel en 1953,* pp. 107–114, Stockholm (1954).
12. F. Zernike, ''The concept of degree of coherence and its applications to optical problems,'' *Physica* **5,** 785–795 (1938). Reprinted in *Selected Papers on Coherence and Fluctuations of Light,* L. Mandel and E. Wolf, Eds., SPIE Press **MS19,** 100–110, Bellingham, WA (1970).
13. P. H. van Cittert, ''Die wahrscheinliche Schwingugsverteilung in einer von einer Lichtquelle direct oder mittels einer Linse beleuchteten Ebene,'' Physica **1,** 201–210 (1934); ''Kohärenz Probleme,'' Physica **6,** 1129–1138 (1939). Reprinted in Selected Papers on Coherence and Fluctuations of Light, L. Mandel and E. Wolf, Eds., SPIE Press **MS19** 1–10, Bellingham, WA (1970).
14. M. Born and E. Wolf, *Principles of Optics,* p. 522, Pergamon Press, Oxford (1970).
15. E. Wolf, ''Some recent research on optical coherence,'' in *Huygens' Principle 1690–1990,* H. Blok, H. A. Ferwerda, and H. K. Kuiken, Eds., pp. 113–127, North-Holland, Amsterdam (1992).
16. B. R. A. Nijboer, ''The diffraction theory of aberrations,'' Thesis, Groningen (1942).
17. K. Nienhuis, ''On the influence of diffraction on image formation in the presence of aberrations,'' Thesis, Gronigen (1948).
18. F. Zernike, ''Diffraction and optical image formation,'' *Proc. Phys. Soc.* **61,** 158–164 (1948).

Hedzer A. Ferwerda is a professor of technical physics at Groningen University, The Netherlands, in the Institute of Theoretical Physics. He works on problems in the theory of wave propagation: inverse problems in image formation, light propagation through turbid media, and nonlinear media.